LOOP ANTENNA DESIGN

This article presents an analysis of loop antenna characteristics to allow optimizing a design.

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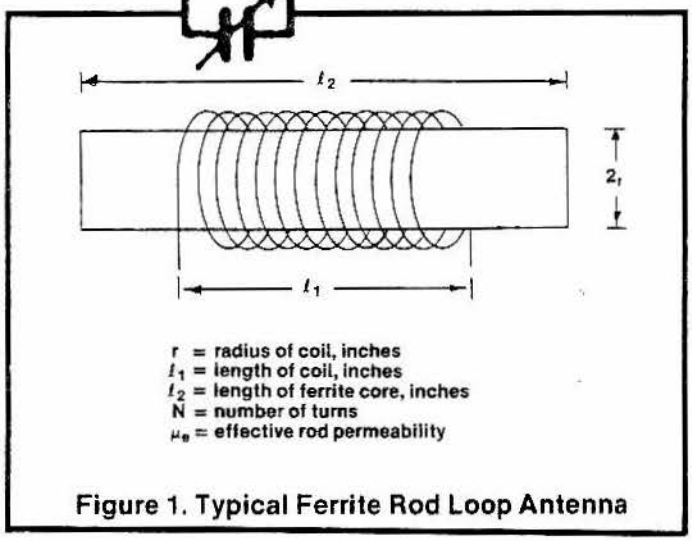

ℓ_2
$2r$
ℓ_1
r = radius of coil, inches
ℓ_1 = length of coil, inches
ℓ_2 = length of ferrite core, inches
N = number of turns
μ_e = effective rod permeability

Figure 1. Typical Ferrite Rod Loop Antenna

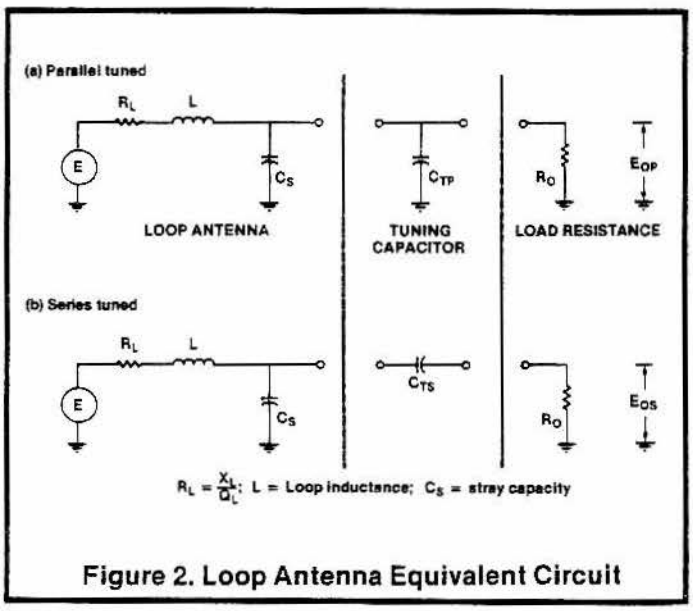


Figure 2. Loop Antenna Equivalent Circuit

There has been comparatively little activity in loop antenna design lately. However, particularly at low frequencies, the loop antenna has several advantages and may be the only viable solution. An example is the near magnetic field used in the early garage door openers[1]. A method will be described suitable for optimizing the design for maximum signal recovery over a specified frequency range or for maximizing the signal to noise ratio. It will be shown that the two designs are not necessarily compatible.

In the actual antenna design three factors, beside the mechanical configuration, have to be considered:

- signal recovery,
- bandwidth,
- signal to noise.

The relative importance of these factors has a pronounced effect on the overall design. Let's consider these factors individually. A ferrite rod loop antenna will be used in the analysis (Figure 1); however, the same analysis applies to air loops.

Signal Recovery

The maximum voltage induced in the loop, E, is:

$$E = 13.55 \times 10^{-12} \mu_e e N A f F_A \text{ volts} \quad (1)$$

where: e = field strength, volts/meter
μ_e = effective rod permeability
N = number of turns
A = area of loop, πr^2, in^2
f = frequency, Hz
F_A = averaging factor

The averaging factor, F_A, is a function of loop configuration. Snelling[2] gives curves of F_A for some typical cases. However, since F_A varies between 1.0 and 0.83 in most instances, a close approximation is:

$$F_A = 1 - 0.17(\ell_1 / \ell_2) \quad (2)$$

The effective rod permeability, μ_e, is a factor of loop dimensions and is often overestimated. Curves of μ_e versus material permeability and form factor are available in the literature[3], but the approximate formula for even very high (>5000) material permeability,

$$\mu_e \approx 2.934\,(\ell_2/2r)^{1.394} \qquad (3)$$

shows that the actual rod permeability is quite small. For instance, for $\ell_2/2r = 10$, maximum possible rod permeability, μ_e, is only about 70.

It is necessary to tune the antenna to maximize the voltage developed across the load (Figure 2). Two possiblities exist: parallel or series tuning.

Parallel Tuning (Figure 2a)

From Figure 3 it can be seen that the circuit gain can be calculated using:

$$\frac{E_{OP}}{E} = \frac{I(R_1 + jX_1)}{E} = \frac{R_1 + jX_1}{R_2 + jX_2} \qquad (4)$$

For circuits with $Q_L > 5$ and $R_0 > 5\,X_c$, this expression is maximized when $X_c = X_L$ (within about 1%). Table I gives a program for the exact calculation of E_{op}/E. (It also calculates the value of C_{TP} in register RO3.) At resonance, for values of Q_L and R_o within the above limits, equation (4) can be simplified to:

$$\left(\frac{E_{OP}}{E}\right)_{max} = \frac{R_O Q_L}{X_L Q_L + R_O} \qquad (5)$$

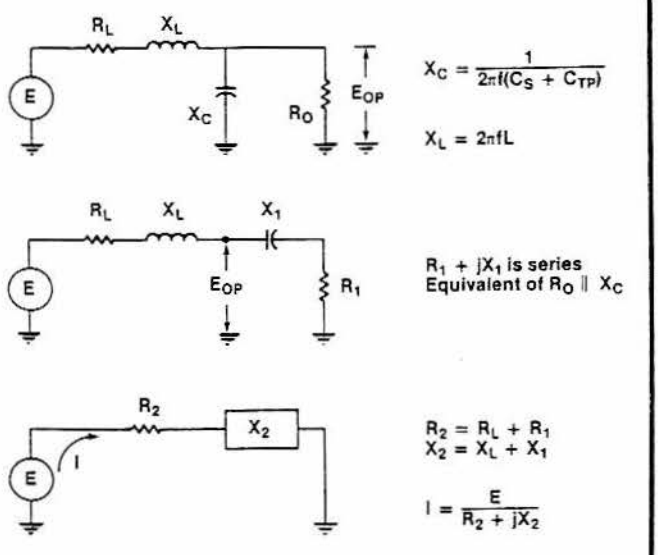


Figure 3. Parallel Tuned Equivalent Circuits

This approximation is within about 5% of the actual gain value, which is adequate for most applications. If the complete circuit Q, Q_O, can be measured, the following resonant gain equation also applies:

$$\left(\frac{E_{OP}}{E}\right)_{max} = Q_O \qquad (6)$$

To illustrate the application of the preceeding equations assume the following conditions:

R_o = 10,000 ohm	ℓ_1 = 7.5 in.
f = 20,000 Hz	ℓ_2 = 8.0 in.
L = 0.037 H	r = 0.625 in.
Q_L = 50	N = 640 turns
C_s = 100 × 10^{-12} F	μ_e = 17
e = 10 × 10^{-6} V/M	F_A(calculated = 0.85 using Eq. 2)

From equation (1) we obtain the loop induced voltage:

$$E = 0.0308 \times 10^{-6}\ \text{volts}$$

Using program of Table I the tuning capacity, C_{TP}, can be calculated:

$$C_{TP} = 1612 \times 10^{-12}\ \text{F}$$

Using equation (4) the exact circuit gain can be calculated:

$$\left(\frac{E_{OP}}{E}\right)_{max} = 2.0617$$

```
01*LBL "LAP 1"
02 RCL 06
03 2
04 *
05 PI
06 *
07 STO 07
08 X↑2
09 RCL 04
10 *
11 1/X
12 RCL 02
13 -
14 STO 03
15 RCL 02
16 +
17 RCL 07
18 *
19 RCL 01
20 1/X
21 R-P
22 1/X
23 P-R
24 STO 08
25 X<>Y
26 CHS
27 STO 09
28 X<>Y
29 RCL 04
30 RCL 07
31 *
32 ST+ 09
33 RCL 05
34 /
35 RCL 08
36 +
37 RCL 09
38 X<>Y
39 R-P
40 1/X
41 X<>Y
42 CHS
43 RDN
44 RDN
45 R-P
46 R↑
47 *
48 RDN
49 /
50 R↑
51 END
```

R00 R01 R02 R03 R04 R05 R06 R07 R08 R09 R10 R11 R12 R13 R14 R15 R16 R17 R18 R19 R20 R21 R22 R23 R24 R25 R26 R27 R28 R29 R30

R_O
C_S
[C_TP]
L
Q_L
f
[2πf]

TABLE I.

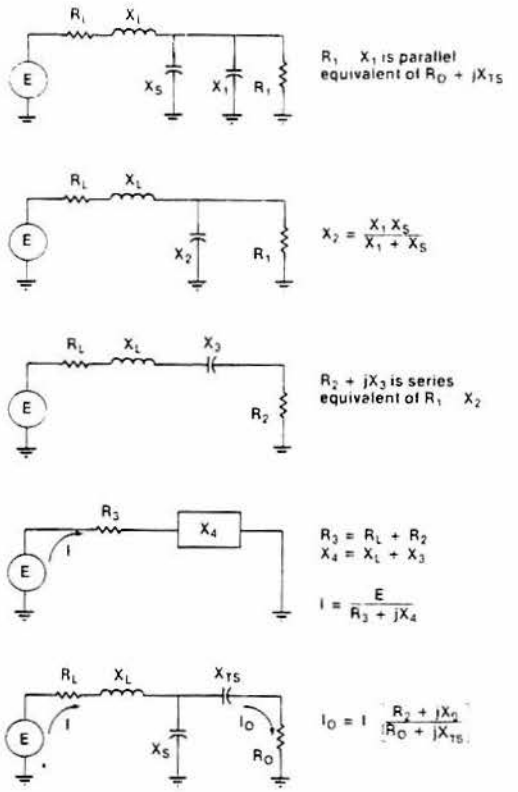


Figure 4. Series Tuned Equivalent Circuits

The approximate gain value using the simplified equation (5) is:

$$\left(\frac{E_{OP}}{E}\right)_{max} = 2.0620$$

or close enough for most applications.

Thus, the recovered voltage across the load, at resonance, is:

$$\left(\frac{E_{OP}}{E}\right)_{max} E = E_{OP} = 0.0635 \times 10^{-6} \text{ volts}$$

```
01*LBL  LH5 1'
02 RCL 06
03 ST+ X
04 PI
05 *
06 STO 07
07 RCL 03
08 *
09 1/X
10 CHS
11 STO 09
12 RCL 01
13 R-P
14 1/X
15 P-R
16 '.'
17
18 '   22
19 RCL 07
20 *
21 CHS
22 +
23 X<>Y
24 1/X
25 R-P
26 1/X
27 P-R
28 STO 10
29 X<>Y
30 STO 11
31 RCL 04
32 RCL 07
33 *
34 STO 08
35 +
36 X<>Y
37 RCL 08
38 RCL 05
39 /
40 +
41 R-P
42 STO 08
43 RCL 09
44 RCL 01
45 R-P
46 ST* 08
47 RCL 11
48 RCL 10
49 R-P
50 RCL 08
51 /
52 RCL 01
53 *
54 .END.
```

R00 RO
R01 CS
R02 CTS
R03 L
R04 QL
R05 f
R06 2πf
R07
R08
R09
R10
R11
R12
R13
R14
R15
R16
R17
R18
R19
R20
R21
R22
R23
R24
R25
R26
R27
R28
R29
R30

TABLE II.

Series Tuning (Figure 2b)

The series tuned circuit can be similarly analyzed. The stray capacity, C_s, complicates calculations somewhat, as shown in Figure 4.

The gain of the circuit is:

$$\frac{E_{OS}}{E} = R_O \left[\frac{R_2 + jX_3}{(R_3 + jX_4)(R_O + jX_{TS})}\right] \quad (7)$$

While it is possible to solve for the value of C_{TS} to maximize the above expression, it is easier to use trial-and-error and the program of Table II. Selected values for C_{TS} are stored in register 03 and the calculation performed until a maximum value of circuit gain is obtained. It can be seen from Figure 2b that with no stray capacity (C_S = 0) the maximum circuit gain occurs when the reactance of C_{TS} is equal to the reactance of L. The maximum circuit gain obtainable under these conditions is always less than unity (unity for infinite Q_L).

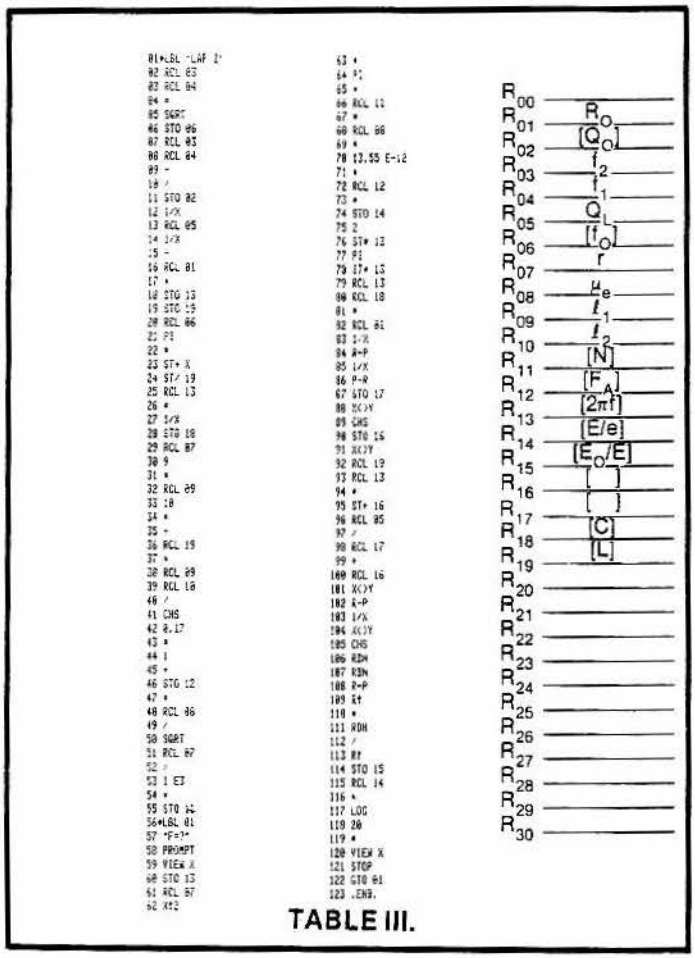
For the same example used to illustrate the parallel tuned case, using equation (7) maximum gain is obtained for C_{TS} = 1612 PF or the same as for the parallel tuned circuit. However, the circuit gain is only 1.0510, or considerably less. For large ratios of C_{TS}/Cs, the value of C_{TS} will be the same as C_{TP} (for the same circuit conditions) and gain will be less. Thus, it would seem that the series tuned circuit is not as desirable as the parallel tuned. That is not necessarily the case, however. It will be shown later that under some conditions the S/N ratio may be higher for the series tuned circuit even though the recovered signal is lower. In some cases, as the value of C_s is artificially increased (and the value of C_{TS} is lowered) a condition of high gain may exist. In the previous example, for instance, when C_s is increased to 1500 PF and C_{TS} is decreased to 215 PF the circuit gain becomes 5.0165, which is considerably more than was obtained in the parallel tuned case.

In the limiting case when C_s is 1612 PF and C_{TS} is infinity we obtain the equivalent parallel tuned circuit and a circuit gain of 2.0617.

Bandwidth

While the signal recovery (effective height) of a loop antenna is important, its bandwidth may be another critical parameter. In some applications tuning of the antenna is either not desirable or possible, and the antenna has to be designed to cover the entire frequency range of interest. For maximum sensitivity the load resistance, R_O, should determine the bandwidth (Q) of the circuit, since additional loading to increase bandwidth would introduce unnecessary losses. The common method is to select a loop antenna and then increase or lower its impedance, by means of a transformer, until the desired performance is obtained. While usually satisfactory, this procedure introduces another critical component, the transformer, which has to be designed with the proper bandwidth. In addition, the transformer itself may introduce stray pick-up, since the operating signal levels are very low.

The procedure described below was satisfactorily used in a low signal level system and does not use a transformer. The antenna is designed to match the load in a manner providing the desired bandwidth.



```
01*LBL "LAF 2"
02 RCL 03
03 RCL 04
04 *
05 SQRT
06 STO 06
07 RCL 03
08 RCL 04
09 -
10 /
11 STO 02
12 1/X
13 RCL 05
14 1/X
15 -
16 RCL 01
17 *
18 STO 13
19 STO 15
20 RCL 06
21 PI
22 *
23 ST+ X
24 ST/ 19
25 RCL 13
26 *
27 1/X
28 STO 18
29 RCL 07
30 9
31 *
32 RCL 09
33 10
34 *
35 +
36 RCL 19
37 *
38 RCL 09
39 RCL 10
40 /
41 CHS
42 8.17
43 *
44 1
45 +
46 STO 12
47 *
48 RCL 06
49 /
50 SQRT
51 RCL 07
52 /
53 1 E3
54 *
55 STO 14
56*LBL 01
57 "F="
58 PROMPT
59 VIEW X
60 STO 03
61 RCL 07
62 X↑2
63 *
64 PI
65 *
66 RCL 11
67 *
68 RCL 08
69 *
70 13.55 E-12
71 *
72 RCL 12
73 *
74 STO 14
75 2
76 ST* 13
77 PI
78 ST* 13
79 RCL 13
80 RCL 18
81 *
82 RCL 01
83 1/X
84 A-P
85 1/X
86 P-R
87 STO 17
88 X<>Y
89 CHS
90 STO 16
91 X<>Y
92 RCL 19
93 RCL 13
94 *
95 ST+ 16
96 RCL 05
97 /
98 RCL 17
99 *
100 RCL 16
101 X<>Y
102 A-P
103 1/X
104 X<>Y
105 CHS
106 RDN
107 RDN
108 P-P
109 R↑
110 *
111 RDN
112 /
113 R↑
114 STO 15
115 RCL 14
116 *
117 LOG
118 20
119 *
120 VIEW X
121 STOP
122 GTO 01
123 .END.
```

R_{00} R_0
R_{01} $[Q_0]$
R_{02} f_2
R_{03} f_1
R_{04} Q_L
R_{05} $[f_0]$
R_{06} r
R_{07}
R_{08} μ_e
R_{09} ℓ_1
R_{10} ℓ_2
R_{11} [N]
R_{12} $[F_A]$
R_{13} $[2\pi f]$
R_{14} [E/e]
R_{15} $[E_0/E]$
R_{16} [ ]
R_{17} [ ]
R_{18} [C]
R_{19} [L]
R_{20}
R_{21}
R_{22}
R_{23}
R_{24}
R_{25}
R_{26}
R_{27}
R_{28}
R_{29}
R_{30}

TABLE III.

Parallel Tuning

While the voltage induced in the loop increases with frequency (Equation (1)), the parallel tuned loop antenna equivalent circuit has basically a lowpass filter configuration (Figure (2a)). Thus these two effects can be made to produce an overall bandpass effect.

While it is possible to use a trial-and-error procedure and the program of Table I, it is more convenient to obtain all the design data from the program of Table III. Using as inputs the physical characteristics of the loop, the center frequency, the required circuit Q (a function of bandwidth), the expected coil Q, and the load resistance, the program gives the number of turns, the coil inductance and the total tuning capacity ($C_s + C_{TP}$). First the center frequency is calculated. As with most filters, the geometric mean gives the best results:

$$f_o = \sqrt{f_2 f_1} \tag{8}$$

Then circuit Q is calculated

$$Q_o = \frac{f_o}{f_2 - f_1} \tag{9}$$

Using (8) and (9) and

$$X_L = R_o\left(\frac{1}{Q_o} - \frac{1}{Q_L}\right) \tag{10}$$

and

$$L = \frac{X_L}{2\pi f_o} \tag{11}$$

the program calculates the inductance of the coil, L, and stores it in register 04. The required number of turns is then calculated using:

$$L = \mu_e F_A \frac{(rN)^2}{9r + 10\ell_1} \times 10^{-6}\ H \tag{12}$$

and is stored in register 11. The total tuning capacity is also calculated and stored in register 18. LBL 01 of the program will then calculate the voltage induced in the loop for a given field strength (E/e), store it in register 14, calculate circuit gain (E_o/E), store it in register 15 and finally calculate the overall "gain" (E_o/e) in dB. (While it is not strictly correct to express E_o/e in dB, since the units for E_o and e are not the same, it is convenient for overall system calculations.) By repeating LBL 01, for different frequencies, a complete frequency response can be obtained.

Let us consider the following example:

f_2 = 30 KHz
f_1 = 10 KHz
R_o = 5000 ohm
ℓ_1 = 7.0 inches
ℓ_2 = 8.0 inches
r = 0.375 inches
μ_e = 60
Q_L = 10

Using program of Table III we obtain:

f_o = 17.32 KHz (REG 06)
Q_o = 0.866 (REG 02)
L = 0.0485 H (REG 19)
C = 1742 × 10^{-12} F (REG 18)
N = 599 turns (REG 11)

Using LBL 01 of Table III, the frequency response can be then calculated, and is shown in Table IV. The calculated frequency response is within < 0.2 dB of that required, which is quite adequate for this large a bandwidth.

Series Tuning

Series tuned antenna does not provide a suitable bandpass response. The E/e response is the same as for the parallel tuned case, but E_o/E has a bandpass characteristic; thus, the overall response has a highpass rather than bandpass shape. This is shown in Figure 5. The same loop antenna as in the above example was used. The total capacity of 1742 PF was divided into C_s = 100 PF and C_{TS} = 1642 PF. The calculated response using equations (1) and (7) is shown in Table V.

Frequency	E/e	E_o/E	E_o/e(dB)	Freq. Resp. (dB)
5000 Hz	9.16×10^{-4}	1.00	−60.74	−9.48
10,000	1.83×10^{-3}	1.03	−54.49	−3.23
15,000	2.75×10^{-3}	0.96	−51.61	−0.35
17,320	3.17×10^{-3}	0.86	−51.26	0 (ref)
20,000	3.66×10^{-3}	0.73	−51.44	−0.18
25,000	4.58×10^{-3}	0.51	−52.65	−1.39
30,000	5.49×10^{-3}	0.36	−54.14	−2.88
35,000	6.41×10^{-3}	0.26	−55.53	−4.27

Table IV. Parallel Tuned Antenna Frequency Response.

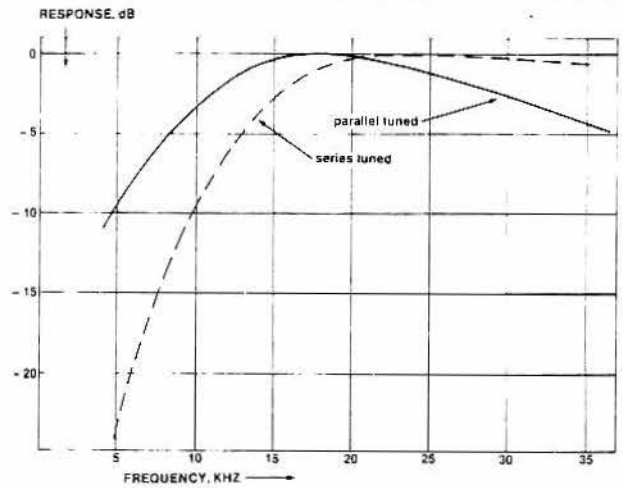


Figure 5. Compairson of Parallel and Series Tuned Antenna Response

Signal to Noise Ratio

So far only the signal recovery characteristics of a loop antenna were considered. In most cases, however, the signal to noise ratio of the recovered signal is of more importance. To simplify the analysis, a noiseless amplifier is assumed, the amplifier input thermal noise being generated in the input resistance R_o. To permit a complete analysis "noise" has to be also defined. Dr. Hubert[4] points out that noise in RLC circuits is not in general white and has to be integrated over the bandwidth of interest:

$$\varrho_n = \sqrt{\int_{\omega_1}^{\omega_2} \overline{i_n}^2 |Z_T(\omega)| d\omega} \qquad (13)$$

where $\overline{i_n}^2$ = total noise current density, A^2/Hz

$Z_T(\omega)$ = total impedance (function of frequency)

Since the bandwidth of interest is not necessarily the noise bandwidth of the antenna circuit, noise density rather than total noise will be used in signal to noise calculations. This is reasonable, since these antennas are often used to receive several narrow band signals (later separated by filters) and the total noise over the narrow bandwidth can be closely approximated by multiplying the noise density by $\sqrt{\text{bandwidtn}}$. Again, the parallel tuned and the series

Frequency	E_o/E	E_o/e(dB)	Freq. Resp. (dB)
5000 Hz	0.27	– 72.12	– 22.75
10,000	0.60	– 59.16	– 9.79
15,000	0.91	– 52.05	– 2.68
17,320	0.95	– 50.44	– 1.07
20,000	0.91	– 49.59	– 0.22
25,000	0.74	– 49.37	0 (ref)
30,000	0.60	– 49.62	– 0.25
35,000	0.50	– 49.87	– 0.50

Table V. Series Tuned Antenna Frequency Response.

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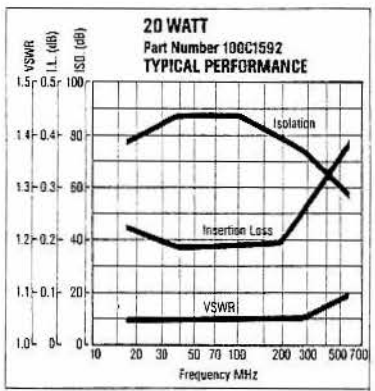
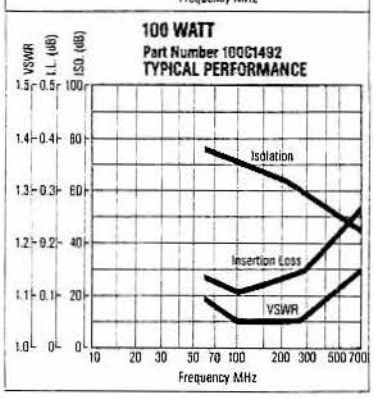
RF SOLID-STATE SWITCHES



Specifications
20 WATT P/N 100C1592
Configuration: SP2T
Frequency: 20-500 MHz
RF Power: 20 WATT CW
Control: 1 Line TTL
Switching
Speed: 10 µsec. Max.
DC Power: +5V at 220 mA
−15V to −30V
at 20 mA
Impedance: 50 Ohms
Connectors: SMA
Size: 2.75" x 3" x 1.4"



Specifications
100 WATT P/N 100C1492
Configuration: SP2T
Frequency: 100-500 MHz
RF Power: 100 WATT CW
Control: 1 Line TTL
Switching
Speed: 30 µsec. Max.
DC Power: +5V at 300 mA
−50V at 10 mA
Impedance: 50 Ohm
Connectors: N
Size: 4" x 4.75" x 1.3"

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INFO/CARD 8

```
01♦LBL "LAP 3"      23 CHS
02 RCL 06           24 +
03 ST+ X            25 RCL 01
04 PI               26 1/X
05 *                27 RCL 08
06 STO 07           28 +
07 RCL 04           29 R-P
08 *                30 1/X
09 STO Y            31 RCL 01
10 RCL 05           32 1/X
11 /                33 RCL 08
12 R-P              34 +
13 1/X              35 4
14 P-R              36 *
15 STO 08           37 1.38 E-23
16 1/X              38 *
17 X<>Y             39 300
18 RCL 02           40 *
19 RCL 03           41 SQRT
20 +                42 *
21 RCL 07           43 .END.
22 *
```

R_{00} R_O, R_{01} C_S, R_{02} C_{TP}, R_{03} L, R_{04} Q_L, R_{05} f, R_{06} $[2\pi f]$, R_{07} [ ], R_{08} – R_{30}

TABLE VI.

```
01♦LBL "LAP 2"      28 1/X
02 RCL 06           29 -
03 ST+ X            30 X<>Y
04 PI               31 R-P
05 *                32 1/X
06 STO 07           33 P-R
07 RCL 04           34 STO 08
08 *                35 RDN
09 STO Y            36 RCL 01
10 RCL 05           37 1/X
11 /                38 RCL 08
12 R-P              39 +
13 1/X              40 R-P
14 P-R              41 1/X
15 X<>Y             42 RCL 01
16 RCL 02           43 1/X
17 RCL 07           44 RCL 08
18 *                45 +
19 -                46 4
20 X<>Y             47 *
21 R-P              48 1.38 E-23
22 1/X              49 *
23 P-R              50 300
24 X<>Y             51 *
25 RCL 03           52 SQRT
26 RCL 07           53 *
27 *                54 .END.
```

R_{00} R_O, R_{01} C_S, R_{02} C_{TP}, R_{03} L, R_{04} Q_L, R_{05} f, R_{06} $[2\pi f]$, R_{07} [ ], R_{08} – R_{30}

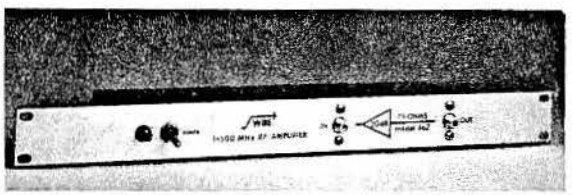
TABLE VII.

tuned antenna will be considered separately. As an example let's assume the following conditions:

R_o = 10,000 ohm
$C_s = 100 \times 10^{-12}$ F
$C_{TP} = C_{TS} = 1768 \times 10^{-12}$ F
$L = 15.5 \times 10^{-3}$ H
Q_L = 20
r = 0.375
μ_e = 60
ℓ_1 = 7
ℓ_2 = 8
N = 339

(These figures were obtained using program of Table III and f_1 = 25,000 Hz and f_2 = 35,000 Hz to obtain a representative antenna design). The requirement is to determine the signal to noise ratio at several frequencies over the antenna pass-band with a field strength of 100 microvolts per meter, and a noise bandwidth of 100 Hz. Since the antenna bandwidth is rather large and the noise bandwidth small, the proposed

A52U UHF RF SWEEP AMPLIFIER



Similar in appearance to the A62 RF Sweep Amplifier pictured, the A52U RF Sweep Amplifier has a frequency range of 1-900 MHz. Flatness is ±.5 dB. Gain is 30 dB nominal. Input VSWR is 1.5:1 max with typical VSWR of 1.2:1. Available in 50 or 75 ohm impedance, the unit is an excellent general purpose lab amplifier amplifying signals for receivers, frequency counters, spectrum analyzers, oscilloscopes, markers and detectors. It is rugged enough for mobile applications. Line filtering and double shielding prevent ambient and power line interference.

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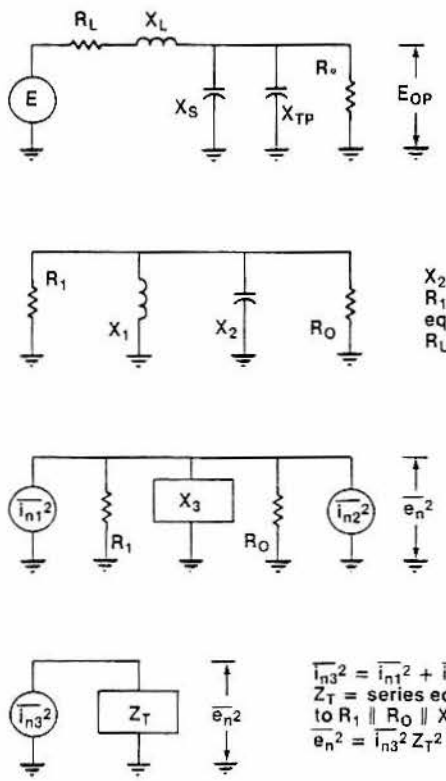


Figure 6. Parallel Tuned Antenna Equivalent Noise Circuit

Frequency	E_O/e	Signal	Noise	S/N
25,000 Hz	– 43.96 dB	6.35×10^{-7}	8.44×10^{-9}	37.53 dB
29,600	– 40.86	9.05×10^{-7}	1.19×10^{-8}	37.62
30,000	– 40.88	9.04×10^{-7}	1.18×10^{-8}	37.69
35,000	– 43.80	6.45×10^{-7}	8.37×10^{-9}	37.74
20,000	– 49.15	3.49×10^{-7}	4.74×10^{-9}	37.34
40,000	– 47.13	4.40×10^{-7}	5.66×10^{-9}	37.81

Table VIII. Parallel Tuned Antenna Signal and Noise Characteristics.

approximation of calculating signal to noise density ratio and multiplying by $\sqrt{100}$ should be valid.

Parallel Tuning

The method of calculating the recovered signal has been already described. To calculate the noise voltage density, the total noise current density and total impedance method[4] will be used. The method of arriving at the parallel tuned loop antenna equivalent noise circuit is shown in Figure 6. Series-parallel and parallel-series transformations are used to allow simplification of the circuit. The noise voltage density, at any given frequency, is

$$\overline{e_n} = \overline{i_n}|Z_T| \qquad (14)$$

The program of Table VI simplifies the calculations. The results are shown in Table VIII. (The signal levels were calculated using previously shown methods). From these

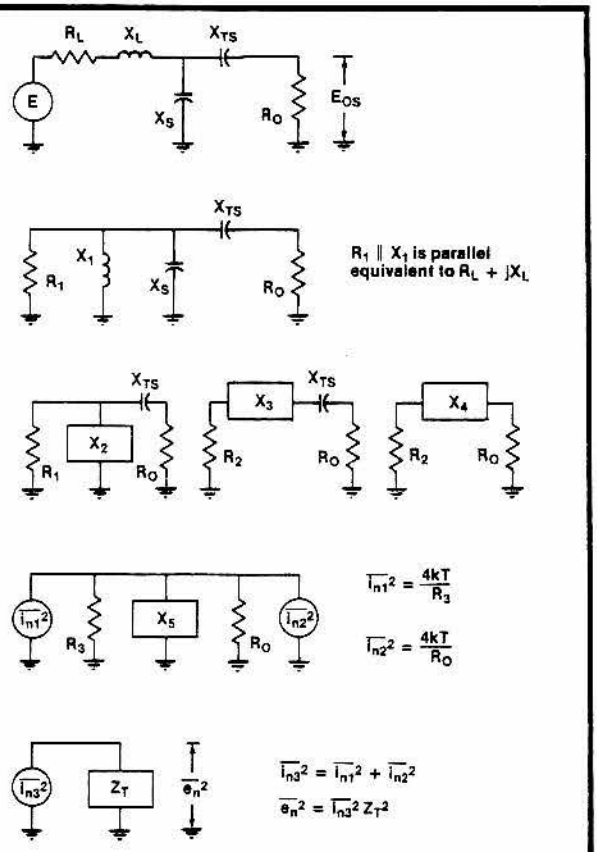
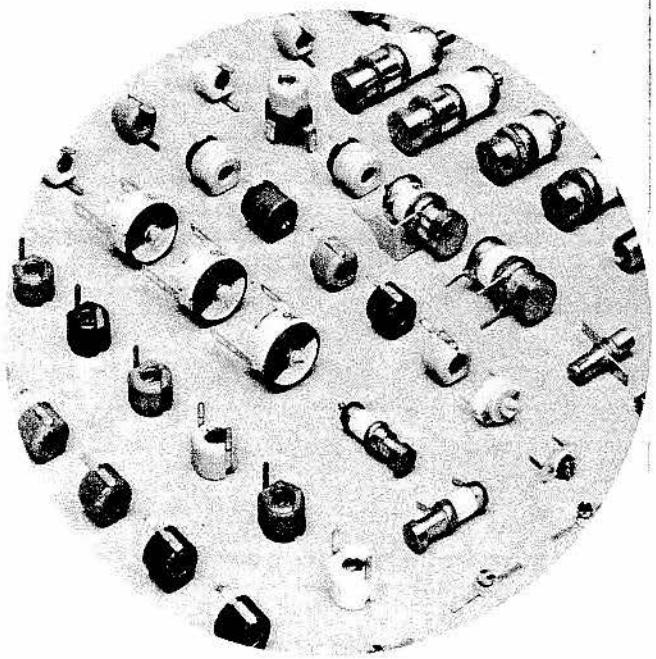


Figure 7. Series Tuned Antenna Equivalent Noise Circuit



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Frequency	E	E_O/E	Signal	Noise	S/N
25,000 Hz	2.59×10^{-7}	1.02	2.64×10^{-7}	1.99×10^{-9}	42.46 dB
29,600	3.07×10^{-7}	1.04	3.19×10^{-7}	1.62×10^{-9}	45.89
30,000	3.11×10^{-7}	1.04	3.24×10^{-7}	1.64×10^{-9}	45.91
35,000	3.62×10^{-7}	1.05	3.81×10^{-7}	2.27×10^{-9}	44.50

Table IX. Series Tuned Antenna Signal and Noise Characteristics.

Frequency	E_O/E	Signal	Noise	S/N
25,000 Hz	1.00	2.59×10^{-7}	3.43×10^{-9}	37.56 dB
29,600	1.00	3.07×10^{-7}	4.01×10^{-9}	37.68
30,000	1.00	3.11×10^{-7}	4.06×10^{-9}	37.68
35,000	1.00	3.62×10^{-7}	4.69×10^{-9}	37.75

Table X. Untuned Antenna Signal and Noise Characteristics.

results it can be seen that the expected S/N ratio for a 100 microvolt/meter signal and 100 Hz bandwidth will be in the 17-18 dB range. Note that while the signal peaks in the middle of the antenna bandwidth, so does the noise, and the resultant S/N remains quite constant.

Series Tuning

The calculation of noise voltage density for the series tuned antenna is more complicated because of the stray capacity, C_s. However, the same method of circuit simplification can be used, as shown in Figure 7. The program of Table VII performs the required calculations. Using our example the figures shown in Table IX can be obtained. Using the series tuned antenna, the noise dips in the middle of the passband and is lower than in the parallel tuned case resulting in higher S/N even though the recovered signal is lower. The expected S/N for the 100 Hz bandwidth of the example will be in the 22-26 dB range over the 25-35 KHz frequency range.

Untuned Antenna

In view of the somewhat unexpected results, it may be interesting to see how an untuned antenna would perform. The calculations can be performed using the series tuned antenna programs and a large value for C_{TS} (1 F, for instance). The results are shown in Table X. The resultant S/N characteristics are very similar to the parallel tuned case; however, both signal and noise levels are lower.

Summary

The presented analysis of loop antenna characteristics indicate that, in general, one should not generalize in loop antenna design, but each case should be individually examined and all pertinent factors considered.

Some trends are apparent, however, and are shown in Table XI. These should be used with caution, confirming the characteristics with actual calculations. In addition, the following characteristics should also be considered in the circuit design, but also only as starting points:

- If a well controlled broadband 3dB passband signal "gain" (output voltage/field strength) is required consider the parallel tuned design.
- If maximum S/N is required for narrow band channels give the series tuned design a try.
- If a constant S/N for several narrowband channels is needed, the parallel tuned or untuned designs may be best.
- While the bandwidth of a parallel tuned antenna (in terms of signal recovery) is well defined, its S/N bandwidth (constant S/N for narrowband channels) is much larger.
- Because of the above characteristic, the parallel tuned loop antenna bandwidth can be made quite large by shaping frequency response after first low level amplification, since this would have no effect of S/N.
- To increase gain-bandwidth maximize E/L ratio. □

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	UNTUNED	PARALLEL TUNED	SERIES TUNED
SIGNAL RECOVERY	Lowest (increases with frequency)	High (peaks in middle of passband)	Low (increases with frequency)
NOISE DENSITY	Low (increases with frequency)	High (peaks in middle of passband)	Lowest (dips in middle of passband)
S/N	Low (constant with frequency)	Low (constant with frequency)	High (varies with frequency)

Table XI. Trends in Loop Antenna Characteristics.